GEOACOUSTIC MODELS OF THE SEA FLOOR. 1. SHALLOW BERING SEA; 2. MOHOLE (GUADALUPE SITE)

Information and technology involved in deriving models of two contrasting locations, in first of projected series

E. L. Hamilton • **Research and Development** • **19 April 1965**

U. S. NAVY ELECTRONICS LABORATORY, SAN DIEGO, CALIFORNIA 92152 • A BUREAU OF SHIPS LABORATORY

THE PROBLEM

Determine and study those characteristics of the sea floor that affect the propagation of acoustic energy in the sea. Facilitate such studies by specifying what information is needed for a geoacoustic model of the sea floor.

RESULTS

1. It was determined that an ideal model of the sea floor in an area of experimental underwater sound propagation should include:

a. A detailed topographic chart based on electronically determined ship's positions.

b. Information on sub-bottom layering within the upper tens of feet.

c. Sufficient measurements, from both laboratory and *in situ* (in boreholes or from submersibles) studies to establish the vertical and horizontal variations in those properties of sediments having to do with sound propagation.

2. Geoacoustic models of certain shallow-water portions of the Bering Sea, and of the site of the 1961 Experimental Mohole drilling east of Guadalupe Island, Mexico, were prepared, incorporating new information being used at NEL in studies of underwater sound propagation. These two models contrast strongly; the Bering Sea area has a shallow-water, high-velocity, hard-sand bottom, while the Mohole area has a deep-water, low-velocity, soft-clay bottom. Sediment samples from both areas were tested for sound speed and related properties; laboratory measurements were corrected to *in situ* values.

RECOMMENDATIONS

1. Provide a realistic model of the sea floor for experimental and theoretical studies, whenever underwater sound experiments involve bottom-bounce propagation.

2. In future geoacoustic models, include detailed data on the sub-bottom layering for the first few tens of feet.

3. Devote theoretical and experimental study to (a) mass physical properties of the sediments -- such as the velocity of the elastic shear wave and attenuation of the compressional wave at the frequencies most used in sonar technology -- and (b) the vertical gradient of sound velocity in the upper sediments.

4. Facilitate the prediction of geoacoustic properties by investigating sedimentary processes and areal distributions of sediments.

ADMINISTRATIVE INFORMATION

Work was performed under SR 004 03 01, Task 0539 (NEL L40151), as assigned by BuShips ltr ser 341-065 of 30 Sept 60, by members of the Marine Environment Division. The report covers various field work and laboratory studies since 1960; especially, work done in the Bering Sea in 1960, and on sediments from the Experimental Mohole (Guadalupe Site). The report was approved for publication 19 April 1965. It is the first of a projected series of geoacoustic models of many areas.

Suggestions and criticism from G. H. Curl, K. V. Mackenzie, E. C. LaFond, D. G. Moore, and E. C. Buffington are appreciated.

Biological samples were taken and preserved by John Tibbs of the University of Southern California, working under ONR Contract 228/19/NR 107-567; arrangements for his participation in the project were made by B. K. Couper of BUSHIPS and Dr. S. R. Galler of ONR.

CONTENTS

TABLES

ILLUSTRATIONS

INTRODUCTION

In underwater acoustics studies related to undersea warfare, an understanding of underwater sound transmission and effects such as reverberation, attenuation, reflection, and refraction is indispensable. Such knowledge is also used in geophysical research; data on refraction and reflection of elastic waves through and from the sea floor are invaluable in determining the structure of the earth's crust.

In either of these applications, studies of the sea floor are greatly facilitated by a geoacoustic model: a plan and cross section of a specific geographic area of the sea floor, accompanied by tables and graphs indicating those properties and characteristics of the sediment, rock, and water which are of importance to the behavior of underwater sound.

In the past there has been a variety of models, many with a tenuous (or no) relation to any real sea floor.[1] Such models are useful in many rigorous solutions, but in special applications to a particular sea-floor environment it is necessary to know the outside limits of the more important parameters, such as sound velocity or density.

Geoacoustic models incorporating information gained in support of underwater sound experiments and other studies conducted by the U. S. Navy Electronics Laboratory are to be covered in a projected series of reports, of which this is the first. The models to be described here involve (1) certain shallow-water portions of the Bering Sea, and

---

[1]Superscript numbers identify references listed at end of report.

(2) the site of the 1961 Experimental Mohole drilling east of Guadalupe Island, Mexico. Subsequent reports will bear the same title except for the area involved; some will be classified under applicable security regulations, but many will be unclassified. For each location there will be references to literature covering NEL acoustics studies in the area. When the present backlog of information has been reported, future information will be reported as it is obtained. It is hoped that the series will be of interest and value to persons studying the acoustics or geology of the areas covered.

REQUIREMENTS FOR A MODEL

A thorough discussion of the requirements for an ideal geoacoustic model is not possible within the scope of this report. Briefly summarized, they are as listed below.

1. A detailed topographic chart of the insonified area, based on soundings made by a research-type echo sounder, and with the location of the ship electronically determined.

2. Sub-bottom layering of the sediments and rocks.

   a. Detailed layering on the order of a few tens of feet.

   b. General layering to several hundreds of meters.

3. Sediment and rock samples.

   a. Enough sediment and rock samples to define, in detail, the lateral and vertical sediment and rock distributions at the surface and within each layer.

   b. Observations of the bottom to note the detailed microrelief and material (biological or mineral) which might litter the sediment surface.

4. Mass physical properties of the sediment and rock.

a. The mass physical properties having effects on acoustic transmission (such as sound speed and attenuation at various frequencies; density; porosity; and elastic properties) and their lateral and vertical gradients. Appendix A details these sediment properties.

5. Miscellaneous.

a. The vertical sound-velocity gradient (in microdetail) in the sea water for several hundred meters above the bottom.

b. Chemical properties of the bottom water.

c. Physical chemistry of the sediment and rock masses (including pore water) and the mineralogy of the constituents.

d. Heat-flow measurements within the sediment body.

All of these items, of course, can never be fully determined for any actual segment of the sea floor, especially in deeper waters. In subsequent sections, general information on some of these items will be summarized in tables or short statements; the specific areas under consideration will be described more fully.

METHODS OF CONSTRUCTING A MODEL

Chart Production

Echo sounding and ship positioning are essential to production of any chart, and the worth of the chart is a direct reflection of the care and techniques employed. Any chart not based on information gained by electronic ship positioning is almost certainly in serious error in rough terrain.

Sub-Bottom Layering

Sound penetration of the sea floor and subsequent recording by echo sounder have been known for some decades, but the successful production of instruments to record sub-bottom reflecting layers is no more than 10 years old (excepting explosive seismology, in which travel times are used to postulate models). An excellent resumé of the techniques and instruments available through 1962 is by Hersey.[2]

As higher power and lower frequency are used, the sound penetrates deeper into the sea floor. Each type, or class, of reflection equipment has its own uses, which may overlap but do not, essentially, compete. The echo sounder under very favorable bottom conditions (*i.e.*, a good reflector at relatively shallow depths beneath porous silts and clays) can show a sub-bottom to depths as great as 50 meters, although depths to 20 meters are more common.[3] The Sonoprobe type will operate from a surface vessel in water depths to about 1200 feet and will penetrate 50 to 100 feet (or sometimes more) of sand and softer silts and clays, and will, in some cases, penetrate soft rock and show bedding surfaces.[4] The spark-source type, operating with high power, will penetrate 1 to 3 kilometers, and explosive-source seismic equipment is used to depths of 5 kilometers or more within the earth's crust.[2] It is important to remember that the spark-source equipment may record at the water-sediment interface only a black line which includes several tens of meters of surficial sediment, of interest to only some aspects of underwater sound and geophysics. In other words, the correct instrument must be selected for the data required.

It has been noted that pingers, operating at 12 kc/s on equipment lowered to the bottom (*e.g.*, cameras, corers), frequently record reflecting layers below the water-sediment interface when the ship's echo sounder does not. A promising, possible method of future sub-bottom acoustic reflection surveying could be the attachment of special-purpose pinger transducers to lowered equipment in areas being studied for acoustic experiments. Some

future developments in this field, of interest to underwater acoustics, will probably involve better sound sources, used from research submersibles running close to the sea floor, and deep-towed transducer packages. Information so derived, when combined with drilling into the sea floor, will yield realistic, detailed information on layers within the sea floor.

Sediment and Rock Samples

Two types of samples can be used in the production of acoustic models. For measurements of sound speed and attenuation, density, and some other properties, a "least disturbed" type of sample is needed. These are best obtained by special corers and snapper-type samplers from ship or submersible, or by diving in shallow water. Enough *in situ* measurements should be made to validate the laboratory measurements and their relationships to *in situ* values.[5] Coring can produce samples from the sediment surface to depths of a few meters, but for deeper values it is now necessary to extrapolate or use samples from holes drilled into the bottom (such as the Mohole).

A second type of sample is usable to determine lateral distributions. This can be a seriously disturbed sample on which no more than identification tests need be made (e.g., analysis of grain size and constituents, and density). In any given area, disturbed samples can be used in theoretical and experimental studies to help determine limits of physical properties. For example, the sand from the shallow Bering Sea was used to determine the outside limits of porosity with this particular sediment.

Mass Physical Properties of Sediments and Rocks

A great deal of theoretical and experimental work has been done on sediments and rocks to determine such properties as sound speed, density, porosity, grain size, and mineral constituents. Much of this information is found in

oil-exploration and civil-engineering literature because of industrial interests.

Unfortunately, when the physicist studying the results of underwater sound experiments requires knowledge of the physical properties of the sea floor for any given area, he usually finds that the geologist or geophysicist can only postulate approximate models with limits to the ranges of the more common physical properties, and does not have measurements and related theoretical work to report for his use. The ultimate result of the work presently in progress at several institutions will allow prediction (within reasonable limits) of various properties of the sea floor. A recent general summary of sediment distributions, and ranges of some of the more common physical properties, are indicated in tables 1 and 2 (compiled at the request of a committee of the American Geological Institute). These tables are of interest in defining limiting values of the physical properties noted.

One of the problems in measuring the acoustic properties of sediments in the laboratory is to expel, or keep out, gas or air, especially if an artificial sediment is used in the experiments. If natural sediments are used, and they contain organic matter, the measurements must be made immediately, before gas is generated. If the *in situ* sediments contain gas, as they do in many bay, estuary, or near-shore environments, then valid measurements can probably be made only *in situ*. A plot of sound speed versus percentage of water saturation indicates immediately whether there has been experimental difficulty with gas or air. If the sound speeds at 100 percent saturation are significantly less than about 1500 m/sec for sand, for example, almost certainly there has been difficulty with air or gas within the pores of the sediment structure. It should be noted, however, that many such studies (especially in civil engineering) are intended to show the effects of partial saturation and their validity in this respect is not questioned.

Because of the various difficulties of getting a really good, relatively undisturbed sample back to the laboratory,

TABLE 1. SOME GENERAL CHARACTERISTICS OF SEA FLOOR SEDIMENTS*

Type	Environment	Area Covered (%)	Depth Distrib. (m)	Rates of Deposition (cm/1000 yrs) Max.	Min.	Avg.	Grain Size (med. Diam; mm)
Terrigenous:		25.8	--				
Sand, silt, clay	shelf	(8.3)	--	39	17	29	0.130
	slope	--	--	--	--	19	0.008
	deep-sea[a]	--	--	--	--	--	0.119
Glacial marine	deep-sea	--	--	--	--	--	--
Coral sand, silt	shelf/slope[b]	(3.0)	< 550	--	--	--	1.0
Volcanic sand, silt	shelf/slope[b]	(0.5)	<4800	--	--	--	0.011
Pelagic:	deep-sea	74.2	--	63.9	0.5	8.8	--
Calcareous oozes:	deep-sea	(35.5)	5500	3.2	0.2	.8-1.0	0.008-
Foraminiferal	deep-sea	(34.9)	--	--	--	--	0.450
Coccolith	deep-sea	(0.6)	--	--	--	--	--
Pteropod	deep-sea		--	--	--	--	--
Siliceous oozes:	deep-sea	(10.4)	--	--	--	--	--
Radiolarian	deep-sea	(8.5)	5300	--	--	--	--
Diatom	deep-sea	(1.9)	3900	--	--	--	0.007
"Red" clay	deep-sea	(28.3)	>3700	0.8	0.03	0.1	0.001

NOTES:

a. Turbidites (turbidity-current deposits)

b. Including slope of islands.

*Tables 1 and 2 published as AGI Data Sheet No. 39.[48] References from the literature are noted in the original publication.

TABLE 2. SOME TYPICAL PHYSICAL PROPERTIES OF SEA FLOOR SEDIMENTS[a]

	Continental Shelf									Deep Sea					
	Sand			Sandy Silt Silty Sand			Silt[c]			Clay[c]			Calc. ooze		
Property	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
Density, saturated, gr/cc[b]	2.10	1.80	1.90	1.90	1.50	1.75	1.85	1.25	1.45	1.80	1.18	1.40	1.95	1.25	1.70
Bulk density, avg. mineral grains gr/cc[d]	--	--	2.65	--	--	2.65	--	--	2.65	2.80	2.40	--	--	--	2.72
Porosity, percent	50	35	45	70	45	55	85	50	73	85	50	77	85	45	60
Sound speed, km/sec[e]	1.79	1.54	1.70	1.63	1.48	1.54	1.56	1.47	1.51	1.60	1.47	1.49	2.05	1.48	--
Shear strength[f], cohesion, gr/cm^2	--	--	--	27	4	12	21	3	11	46	4	17	192	4	87
Sensitivity ratio[f,g]	--	--	--	8	3	5	9	2	5	9	2	5	24	2	7

NOTES:

a. Laboratory; room temp. and pressure; sediment surface; all have exceptions, and intergrade.

b. Density of sea water in situ, ranges from approx. 1.025 gr/cc at surface to 1.05 at greatest depth.

c. Including silty clay and clayey silt.

d. Excluding unusual amounts of heavy minerals.

e. Sediment "surface."

f. Vane shear and compression.

g. "Undisturbed" shear strength divided by remolded, or "disturbed," strength.

future work, where possible, should emphasize *in situ* measurements to parallel, or corroborate, experimental and theoretical work in the laboratory. Where *in situ* measurements are not feasible or possible, a great deal of consideration must go into the collection of "undisturbed" samples.

In reviewing the mass physical properties of sediments which are necessary for some theoretical studies of underwater sound, it is apparent that the elastic properties and the frequency-attenuation relationships are the least known. The speeds of compressional elastic waves and densities are fairly well known, or can be easily measured or estimated (although there is much work to be done to reconcile various theoretical and experimental studies). For the shear modulus (or rigidity) and compressibility values, little can be done at present except to estimate, or extrapolate. The single greatest need now is for valid measurements of the speed of shear waves within natural sea-floor sediments. Given the speeds of the compressional and shear waves, plus the density, all of the other pertinent elastic properties may be computed. Another problem, not yet resolved, is which theoretical elastic body (e.g., Voigt, Maxwell, ideal) best represents a natural sediment under the light pressures of a passing acoustic wave at the frequencies of interest in underwater acoustic studies. There is no such thing as an ideal elastic medium in nature, since the energy of any elastic wave is dissipated through conversion to heat and by other mechanisms. This is especially true of sediments, which vary widely in mass properties and constituents, both horizontally and vertically.

Miscellaneous

A complete model study requires the vertical sound-velocity profile in the sea water above the sea floor. This profile is generally obtained by using Nansen cast data, either in a computer program or in conjunction with tables for the speed of sound in sea water. (These tables are conveniently interpolated and published by the U. S. Navy Oceanographic Office.[6-8]) A less common way, but one to

be encouraged, is by use of velocimeters lowered from the surface. In the future, a promising field of research may be concerned with the microvelocity structure in the water a few meters and tens of meters above the sea floor. *In situ* measurements from deep-diving research submersibles hold much promise for such studies.*

Temperature gradients within the sea floor vary enough from place to place to affect the vertical variations of sound speed; this value must be known in order to estimate vertical sound-velocity gradients.[9] Such data can be obtained for general regions (and some particular regions) from the heat-flow measurements currently being taken by geophysicists in ocean basins.

It is known that sediment overburden pressures affect sound speed and other elastic properties in several ways -- for example, by reduction of porosity, by pressure-chemical effects (inducing more "cementation"), and by inducing a more rigid sediment structure through grain-to-grain pressure.

Anywhere an oil-well type of hole is drilled into the sea floor, an attempt should be made to determine the vertical sound-velocity gradients by well-logging, a standard technique in the oil exploration industry. This was tried, but not accomplished, in the preliminary Mohole drilling operations at the Guadalupe site. Production of more valid geoacoustic models of the sea floor is certainly one by-product to be expected from future holes drilled by the Mohole Project.

---

* LaFond, Mackenzie; personal communication.

GEOACOUSTIC MODEL NO. 1: THE SHALLOW BERING SEA

During July and August 1960, the Navy Electronics Laboratory conducted an expedition to the Bering and Chukchi Seas, primarily to support long-range, shallow-water acoustic studies to be made in the same area several weeks later under the direction of K. V. Mackenzie, then of the NEL Underwater Sound Propagation Branch. The trip was made aboard the Scripps Research Vessel HUGH M. SMITH, which was leased to NEL for the expedition.

During the expedition, radio transmissions were made to the Mackenzie party (at sea, but three weeks behind) concerning sediments and sediment thicknesses over prominent reflectors. This information was provided to permit the group to shift their experimental work if the sea-floor environment was not suitable for their purposes. Transmissions were made using a specially devised, prearranged code which is reproduced in Appendix B for those interested in a similar procedure; it is a useful example of transmission of environmental information by radio along a pre-planned track.

Field Program

The program of the expedition is outlined as follows.

1. GEOLOGIC STUDIES

a. The thicknesses of sediments, layering in the sediments, and the structure of rock beneath the sediments on the shallow-water portions of the continental shelf were the most important of the various studies. Two techniques were used. The Marine Sonoprobe operating between 4 and 8 kc/s, and the "Arcer" operating between 200 and 500 c/s, covered approximately 90 percent of the track. In general, there were 5 to 50 feet of sediment overlying the first prominent reflector (thought to be rock) in the Bering Sea.[10]

In the Chukchi Sea a unique set of records was obtained: there were 0 to 5 feet of sediment overlying folded, tilted, and truncated rock; bedding planes in the rock were quite distinct.[10]

b. Detailed topography along the track was obtained either by traces on the Marine Sonoprobe record, or with the Precision Depth Recorder; these traces, plus the thickness information previously mentioned, show that, because of smoothing by sedimentation, these areas are among the flattest places known on earth.

c. Sediments

Figure 1 shows the sediment distributions in parts of the shallow Bering Sea as established by the expedition and by previous work in the area. The exact track lines are classified.

Fifty-three sediment samples were taken by snapper, corer, or by diver. The sediments of the Bering Sea were dominantly fine and very-fine sand in the eastern portions, and sandy silt and silt in the outer (or western) areas. In the Chukchi Sea the sediment was apt to be a mixture of sand-silt-clay, and gravel. Portions of these sediments were examined in the laboratory for median grain diameter, sediment type, density, porosity, shear strength, and sound velocity and attenuation.

d. Bottom photography

A shallow-water lowered camera devised by C. J. Shipek of NEL was used to make 21 lowerings for photographs of the sea floor. Owing to the turbidity of the bottom water (observed by divers) most of these photographs were not usable.

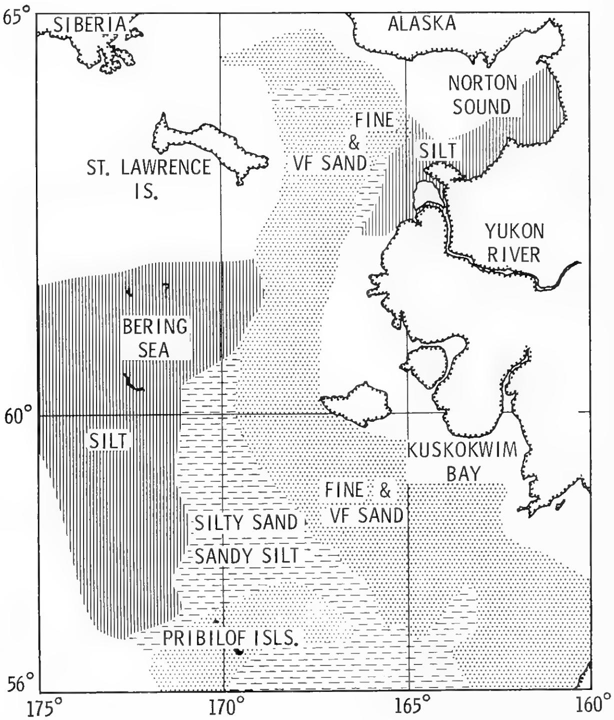

Figure 1. Sediment distributions in parts of the shallow Bering Sea.

2. PHYSICAL OCEANOGRAPHIC STUDIES

a. Sound velocity and water temperature

The velocity of sound in sea water was measured by an NBS-ONR "sing around" velocimeter. Water temperature was measured by an NEL temperature probe and recorder. A technique was devised to tow both of these so that continuous recording could be made along a horizontal track at constant depth. Correlative measurements of vertical water temperature were made by BT every 2 to 4 hours; 176 BT's were taken on the trip. However, the values of water temperature and sound velocity presented in table 3 are those taken a few weeks later by the Mackenzie party, since that group used the acoustic model reported here in their experiments and in the preparation of several reports.

TABLE 3. PROPERTIES OF BOTTOM WATER IN THE SHALLOW BERING SEA (AUGUST 1960)

Location (1)	Depth (m) Sounder	Depth (m) True (2)	Pressure (kg/cm²) (3)	Salinity (°/oo) (4)	Temp. (°C) (5)	Density, in situ (g/cc) (6)	Sound Speed (m/sec) (7)
A	28.7	28.9	3.99	31.8	1.67	1.0257	1452.9
A'	32.3	32.5	4.36	31.8	1.67		1452.9
B	36.8	37.0	4.82	31.2	6.67	1.0247	1473.4
B'	34.2	34.4	4.56	31.2	6.67		1473.4
C	46.9	47.2	5.87	31.8	6.11	1.0253	1472.0
C'	53.3	53.6	6.52	31.8	6.11		1472.1

NOTES:
(1) Location correlates with figures 1 and 2.
(2) True depth computed using water velocity of 1472 m/sec.[49]
(3) Pressure using 1.03 kg/cm^2 for 0 depth and 11.28 kg/cm^2 at 100 m.[50]
(4) Salinity for B and B' from refs. 49 and 51.
(5) Temperatures from D. L. Keir, NEL (personal communication).
(6) Avg.; computed from T, P, S from ref. 52.
(7) Sound speed from ref. 8.

b. Electrical conductivity of sea water

Measurements of the electrical conductivity of sea water were made with a new oceanographic instrument developed at USNMDL, the "Bathyconductograph."

3. SCIENTIFIC DIVING

Thirteen dives (using SCUBA) were made by members of the scientific party. Water temperatures varied from 55°F to 29°F. One dive was made in broken ice under a medium-sized floe. On seven of the dives, Dowling (NMDL) used the AN/PQS-1 (hand-held) sonar to obtain information on the sonar environment and on the existence of false targets; on most of these dives the sonar output was recorded via underwater magnetic-tape recorder to permit comparisons between various environments. One dive was made at Fairway Rock in the Bering Straits; little is known regarding it, however, either geologically or biologically.[11] As was found during the 1958 NEL arctic diving, the use of the specially tailored, $\frac{1}{4}$-inch Neoprene wet diving suits considerably reduced the problem of cold water.[12] One diver was under water of 30°F for a total of $1\frac{1}{2}$ hours in a two-hour time span without undue discomfort. Most of the divers experienced no more discomfort than when diving off Southern California. On most of the dives, bottom sediment and biological samples were taken; visibility typically ranged from more than 50 feet near the surface to less than 3 feet at the bottom.

4. BIOLOGICAL STUDIES

From Kodiak to Pt. Barrow, approximately 60 stations were made at which bottom samples and/or plankton samples were taken. Plankton were taken in two 10-inch nets; bottom samples were taken by snapper and orange-peel bucket, in cores, and by divers; shore collections were made at Kodiak and at St. Paul, Pribilof Islands; collections were made by

divers at St. Paul, St. Lawrence Island, Fairway Rock, and 7½ miles off Kivalina. These large biological collections have been stored at the University of Southern California under the care of Dr. John Mohr, Biology Department.

Results and Conclusions

Immediately after the expedition, a preliminary report of the sea-floor data was made to NEL underwater acoustics personnel, followed by personal consultations. A final report was made on sub-bottom acoustic reflection studies based on the general geology of the area,[10] and data on sediments appeared in several reports and papers.[13-16] Finally the decision was made to publish the sea-floor information in the present form so that interested persons, either in or outside the Laboratory, might have convenient access to it.

In the laboratory the sediments were analyzed and measured for grain size, percentages of sand, silt, and clay, density, porosity, grain density, sound speed, and attenuation (see fig. 2 and tables 3-6). Figure 1, which shows distributions of sediments in parts of the shallow Bering Sea, is a combined chart from earlier work and the samples of the 1960 NEL expedition.[17,18] The profile lines of figure 2 (A-A', etc.) are located in the north, central, and southern shallow Bering Sea; their exact locations are classified.

The values of density and sound speed for the rock underlying the sediments in the shallow Bering Sea are estimates based on geologic assumptions of the rock types present, and the values of sound speed from the literature; they are shown in parentheses in figure 2.

The tables and figures pertain to specific areas or locations and, for the physical properties of the water and sediment, to certain times of the year. This statement is made as a word of caution against using the data for the

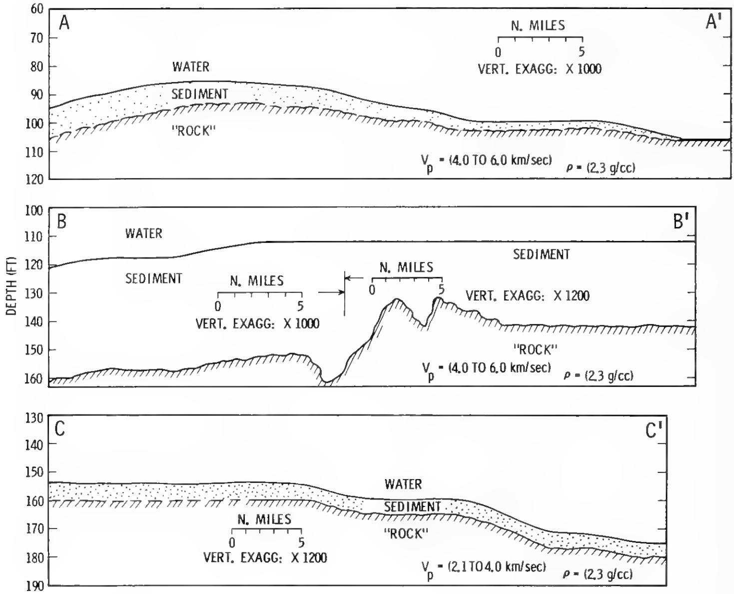

Figure 2. Sediment thicknesses at three locations in the shallow Bering Sea; data from echo-sounding records of the 1960 expedition and the sub-bottom reflection studies of Moore.[12]

whole of the shallow Bering Sea (as the title might imply) and for the whole year. Further assumptions and conditions are noted below each table. For the sediments, it is necessary to enlarge on the method used in the laboratory to obtain porosity (on which the values for sound speed depend). The usual sediment in the areas under consideration was sand. Ordinarily, this material cannot be cored and only by diving can reasonably "undisturbed" samples be obtained. In the laboratory the variations in porosity (which might be expected) were determined by placing actual samples from the area in loose and dense packing; the value noted in the table is estimated to be a probable *in situ* value.

TABLE 4. PHYSICAL PROPERTIES OF SEDIMENTS IN THE SHALLOW BERING SEA

Location (1)	Sediment Type (2)	Median gr. diam (mm)	Sand (%)	Silt (%)	Clay (%)	Density Solids (g/cc) (3)	Density Sat. (g/cc) (4)	Porosity (%) (5)
A-A'	Silty, very fine sand	0.100	63.4	35.9	0.7	2.64	1.84	50
B	Very fine sand	0.101	81.3	18.3	0.4	2.69	1.93	46
B'	Sandy silt	0.060	27.9	71.3	0.8	2.68	1.82	52
C-C'	Very fine sand	0.123	86.6	13.0	0.4	2.69	1.93	46

NOTES:
(1) Correlates with figures 1 and 2 and table 3.
(2) Nomenclature of Shepard.[53]
(3) Pycnometer; avg. of 2 representative bulk samples; ±0.03.
(4) Using porosity variations, density of solids, water density of 1.03 g/cc and equation:

Density, saturated sediments = porosity (density, water) + density, solids (1.0 -porosity).

Variations: A-A': +0.01, -0.12; B: +0.00, -0.13;

B': +0.00, -0.13; C-C': +0.03, -0.10.

(5) Porosity determined by laboratory experiments; that shown is best estimate of in situ conditions.

Variations: A-A': +7, -2; B: +9, -0; B': +8, -0; C-C': +7, -3.

TABLE 5. ACOUSTIC PROPERTIES OF SEDIMENTS IN THE SHALLOW BERING SEA

Location (1)	Sound Speed (m/sec) Lab. (2)	Sound Speed (m/sec) In Situ (3)	Attenuation (dB/ft) (4)	V_2/V_1 (5)	ρV_2 (X 10^5 g/cm² sec) (6)
A-A'	1578	1505	3-6	1.036	2.77
B	1640	1590	3-5	1.079	3.07
B'	1545	1490	4.4	1.012	2.71
C-C'	1640	1590	3-5	1.080	3.07

NOTES:
(1) Correlates with figs. 1 and 2 and tables 3 and 4.
(2) Measured (resonance technique, Shumway): B'; others computed from equation V = 2362 -1568 (porosity), or curves of Shumway.[33, 34, 54]
(3) Lab. values corrected to in situ.[5]
(4) At 24 kc/s; measured (resonance technique, Shumway): B'; others from Shumway.[33, 34]
(5) Sound speed in sediment (V_2) divided by sound speed in bottom water (V_1).
(6) Impedance: sediment saturated density X sediment sound speed in situ.

TABLE 6. COMPUTED (IN SITU) ELASTIC PROPERTIES OF SEDIMENTS IN THE SHALLOW BERING SEA AND IN THE MOHOLE SURFACE *

Location	β Compressibility ($\times 10^{-12}$ cm²/dynes) Solids	Sediment	Water	κ Bulk Modulus ($\times 10^{12}$ dynes/cm²)	σ Poisson's Ratio	μ Shear Modulus ($\times 10^{12}$ dynes/cm²)	V_S (m/sec)
A-A'	1.81	23.183	46.1858	0.0431	0.5	-	-
B	1.79	21.645	44.9534	0.0462	0.48	0.0019	314
B'	1.83	24.254	44.9534	0.0412	0.5	-	-
C-C'	1.83	21.694	45.0125	0.0461	0.48	0.0020	320
Mohole: Surface	(2.0)	34.086	41.6614	0.0293	0.45	0.0029	440

*See text for derivation and discussion; Mohole (Guadalupe Site) gravity core (GGC-3 of tables 7 and 8) included from Model No. 2.

Table 6 lists some computed elastic properties of sands from the shallow Bering Sea. The elastic properties of soils and sediments is a subject receiving increased attention in recent years because of the dynamic, impact loading of missile launch pads, highways, etc. These properties are, of course, the basic parameters for studies of acoustics in sediments and will be the subject of a future paper. For the present, an approach can be made by using the following assumptions, measurements, estimates, and computations, as derived from the author's studies and from the literature.[19-23]

1. A sand has grain-to-grain contacts of randomly-oriented mineral particles. These mineral particles (or crystals), while individually anisotropic as far as elastic properties are concerned, form an aggregate which is isotropic.

2. Sediment structure responds to light pressures (such as a passing sound wave) according to the basic laws and equations of elasticity which adequately describe the elastic properties of rocks, and most solid and liquid substances.

3. Given measurements of the speed of the elastic compressional wave, and the density (saturated), it is necessary to compute, measure, or estimate one other elastic property in order to further compute the remaining elastic properties. In this case the property selected was compressibility, computed by means of the aggregate theory which has been used successfully for rocks of many minerals, solutions of two liquids, and suspensions of mineral particles within a liquid.[19-23] Within the two-phase system (mineral solids and liquid) of the normal marine sediment, the proportional percentages of the compressibilities of the minerals were computed and added from the actual minerals present and their compressibilities as listed in literature.[19,20] The compressibility of the bottom water was computed by using measured values and equation 3. The bulk compressibility of the sediment was then determined by equation 4.

The compressibility for location C-C' was computed from the basic equation

$$V_p = \sqrt{\frac{\kappa + 4/3\mu}{\rho}} \tag{1}$$

V_p in a liquid (having no rigidity) reduces to

$$V_p = \sqrt{\frac{\kappa}{\rho}}, \text{ or } \sqrt{\frac{1}{\rho\beta}} \tag{2}$$

and

$$\left(V_p\right)^2 = \frac{1}{\rho\beta}$$

and

$$\beta = \frac{1}{\rho\left(V_p\right)^2} \tag{3}$$

For line C-C':

$$\beta_w\text{, water} = \frac{1}{1.0253\ \text{g/cc}\ (147{,}200\ \text{cm/sec})^2}$$

$$= 45.0125 \times 10^{-12}\ \text{cm}^2/\text{dynes}$$

$\beta_{sol.}$, mineral solids, bulk $= 1.83 \times 10^{-12}$ cm^2 dynes

$$\beta_{sat.}\text{, bulk, saturated sediment} = (n)\left(\beta_w\right) + (1.0-n)\left(\beta_{sol.}\right) \tag{4}$$

$$= \left[(0.46)(45.0125) + (0.54)(1.83)\right] 10^{-12}\ \text{cm}^2\ \text{dynes}$$

$$= 21.6940 \times 10^{-12}\ \text{cm}^2\ \text{dynes}$$

Where

V_p = velocity compressional elastic wave

κ = bulk modulus, or coeff. of incompressibility

β = compressibility = $1/\kappa$

ρ = density

μ = shear modulus, or modulus of rigidity

n = porosity, or pore spaces, expressed as a fraction of the total volume

4. After the compressibility, $\beta_{sat.}$, was computed, the other elastic properties were computed using the velocity of the compressional wave, V_p, $\beta_{sat.}$, and the density, ρ. The equations favored in these computations were:

$$\sigma = \frac{3.0 - \rho\left(V_p\right)^2 \beta_{sat.}}{3.0 + \rho\left(V_p\right)^2 \beta_{sat.}} \tag{5}$$

$$\mu = \left[\left(V_p \right)^2 \rho - \kappa \right] 3/4 \qquad (6)$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \qquad (7)$$

$$\frac{V_p}{V_s} = \sqrt{\frac{1.0 - \sigma}{0.5 - \sigma}} \qquad (8)$$

Additionally:

$$E = \frac{9 \left[\rho \left(V_p \right)^2 \beta_{sat.} - 1 \right]}{\beta_{sat.} \left[\rho \left(V_p \right)^2 \beta_{sat.} + 3 \right]} \qquad (9)$$

$$\lambda = \kappa - 2/3\, \mu \qquad (10)$$

Where, in addition to notations of (1) to (4):

σ = Poisson's Ratio

V_s = velocity of the shear wave

E = Young's Modulus

λ = Lamé's Constant

GEOACOUSTIC MODEL NO. 2: EXPERIMENTAL MOHOLE (GUADALUPE SITE)*

The sediments cored by the Experimental Mohole Project from the deep-sea floor east of Guadalupe Island, Mexico, during March and April 1961, were divided among a large number of institutions and individuals for various

---

* The substance of this section has been published in reference 24.

investigations. NEL received samples for investigations of shear strength, consolidation, sound speed, and related properties. These sediments are the deepest ever taken from the deep-sea floor and consequently afforded a unique opportunity to define the variations of the sediments and their properties with depth in the sea floor. This section concerns measurements of sound speed and related properties of sediments from Guadalupe Site Hole No. 3 (EM-8), hereafter referred to as "Mohole sediments" or "the drill hole." Other NEL reports concerning these samples are by Igelman and Hamilton, Moore, and Hamilton.[9,25,26]

The deep-sea floor east of Guadalupe Island is gently undulating and the surface sediment is deep-sea ("red") clay,[27] underlain by "hemipelagic" greenish-gray silty clay which could be broadly classified by its constituents as a calcareous-siliceous ooze. The drill hole was at 28° 59' N., 117° 30' W., in a water depth of 11,672 feet (3558 m; fig. 3). The drilling operations have been fully described and much information has been published concerning the sediments in the hole and the basalt cored at a depth of about 560 feet (170 m) beneath the sea floor.[28,29] After the drilling operations, additional reflection surveys have shown the basalt surface to be at varying depths below the water-sediment interface.[30]

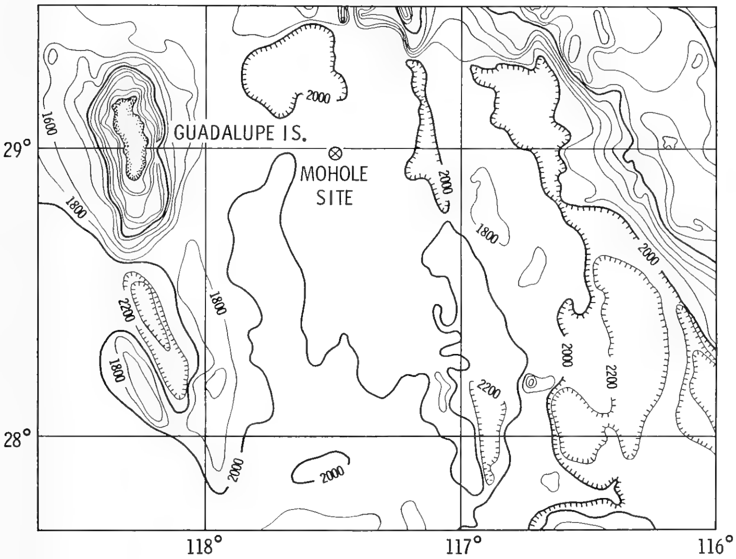

Figure 3. Contoured chart of the sea floor east of Guadalupe Island with the location of the Guadalupe Mohole Site; soundings in fathoms (uncorrected); section of Bureau of Commercial Fisheries Topographic Chart No. 3, 6 May 1960.

Some physical properties of the sediment samples measured for sound speed are listed in table 7. These properties are complementary to the detailed descriptions and classifications of previous papers.[9,26,31,32]

TABLE 7. PHYSICAL PROPERTIES OF 1961 MOHOLE SAMPLES

Sample No. (1)	Depth in Hole (m)	Median Grain Diam. (mm)	Sediment Type	Sp. Gr. Solids (2) (g/cc)	Wet Density (3) (g/cc)		Over-burden Press. (4) (kg/cm^2)
					Lab.	In Situ	
GGC-3	0.6	0.003	Silty clay	- -	1.51	1.51	- -
EM8-1	29.0	0.004	Clayey silt	2.73	1.52	1.55	1.4
EM8-9	77.7	0.004	Silty clay	2.61	1.46	1.51	3.8
EM8-10	86.4	0.003	Silty clay	2.55	1.33	1.36	4.1
EM8-11	96.0	0.002	Silty clay	2.51	1.39	1.40	4.4
EM8-12	105.6	0.002	Silty clay	2.60	1.50	1.55	4.9
EM8-13	114.5	- -	- -	- -	- -	- -	- -
EM8-14	125.0	0.003	Silty clay	2.48	1.41	1.43	5.7
EM8-15	136.3	0.002	Silty clay	2.54	1.45	1.46	6.2

NOTES:

(1) GGC-3 data an average of two samples from gravity core at Guadalupe Site.

(2) Pycnometer; drying at 105°C (avg. of 3).

(3) Wt./volume relationship on wet sample 1" high, 2" to 2½" in diameter; this sample, used in consolidation test, was basis for determination of porosity, void ratio and wet density; "in situ" density from consolidation tests.[9]

(4) Computed from "in situ" densities derived from consolidation tests.

Laboratory Measurements

Sound speed was measured in the laboratory on eight samples from Hole No. 3 (EM-8). The shallowest sample was at 29 meters below the sea floor and the deepest from 136 meters; in addition, sound speed was measured in two samples from a gravity core of the surficial red clay. These sound-speed measurements are listed in table 8. All of the samples were 100 percent saturated at the time of testing.

Four of the measurements were made using the resonant chamber technique.[33,34] These measurements were made by Shumway in April 1961, and have not been previously published; the other six were made by the writer using a pulse technique. All measurements were at one atmosphere of pressure, and the temperature of the sediment at the time of measurement was carefully taken.

TABLE 8. LABORATORY MEASUREMENTS OF SEDIMENT SOUND VELOCITY CORRECTED TO IN SITU VALUES

Sample No.	Laboratory: Sound Velocity (1) (m/sec)	Laboratory: Porosity (%)	In Situ: Temp. (2) (°C)	In Situ: Pressure (3) (kg/cm^2)	In Situ: Porosity (4) (%)	In Situ: Sound Velocity (5) (m/sec)
GGC-3	1496	80.9	1.6	369.2	80.9	1484
EM8-1	1513	71.8	5.6	372.3	69.9	1505
EM8-9	1559	73.1	12.3	377.3	70.6	1593
EM8-10	1533	80.1	13.5	378.2	78.8	1568
EM8-11	1537	76.8	14.8	379.2	75.8	1578
EM8-12	1530	70.5	16.1	380.2	67.4	1580
EM8-13	1533	- -	17.3	381.2	- -	1587
EM8-14	1518	74.6	18.8	382.3	72.6	1573
EM8-15	1522	75.6	20.3	383.4	71.6	1584

NOTES:
(1) Measurements by resonance technique: samples EM8-9, -11, -14, -15, ±10 m/sec; pulse technique: samples GGC-3, 8-1, -10, -12, -13, ±3 m/sec; referred to common temperature of 22.8° C; GGC is Guadalupe Gravity Core.
(2) Measured: in situ sediment surface temperature with increment from gradient (see p. 31).
(3) Hydrostatic (pore water) pressure, water surface to sample level; from Wilson (Table IX, 10° portion for sediment).[50]
(4) From sample consolidation curves.[9]
(5) Laboratory value plus (or minus) the sum of velocity corrections: temperature in lab. (22.8° C) to that in hole; pressure of 1 atmosphere to that in hole; and decrease in porosity, lab. to in situ.

Results and Conclusions

SOUND VELOCITY CORRECTIONS, LABORATORY TO *IN SITU*

While the laboratory sound-speed measurements are of interest, the important aspects of the investigation require that estimates be made of the vertical sound-velocity profile in the sea floor. A study was recently completed in which the bathyscaph TRIESTE was used to measure sound velocities in the surficial sediments off San Diego in water depths to 1235 meters.[5] Cores taken from the TRIESTE at the same places were examined in the laboratory to determine the proper corrections to apply to laboratory measurements to get good estimates of *in situ* sound speeds. These studies showed that predictions within 1 percent accuracy are possible if full temperature and

pressure corrections are made (laboratory to *in situ*) to a sediment sound speed, using Wilson's tables for the speed of sound in sea water.[6,7] An independent verification of the method was obtained when a laboratory measurement on a gravity core sample from the Mohole Site (table 8), when so corrected, was only 3 m/sec from that computed from reflection data in the same area.[35]

These studies with the TRIESTE called attention to the possibilities of applying temperature corrections to vertical sound-velocity profiles within the sediment body. Within the past decade there have been enough studies of heat flow, sediment conductivities, and thermal gradients to allow predictions of this effect in many areas of the oceans. A paper by Gerard et al. gives measurements for the Atlantic, and work by Maxwell, Revelle, Bullard, and Von Herzen, and others has been summarized recently by Bullard.[36,37] Except over ridges, rises, and a few other restricted areas, a representative value for the thermal gradient in the upper sediments is 0.05°C/m. In the Atlantic this gradient is linear in at least the upper 13 meters of sediment.[36] At the Mohole (Guadalupe) Site, a linear gradient of 0.137°C/m was measured through the whole of the sediment section.[38] These gradients are appreciable and are important in studies of the vertical sound-velocity gradient in oceanic sediments, especially when they are as high as that measured at the Mohole Site. In addition to temperature corrections, hydrostatic pressure corrections within the pore water of the sediments can and should be applied.

At the Mohole Site, the temperature in the sediment at the water-sediment interface is 1.6°C; the thermal gradient is 0.137°C/m. At a depth of 100 meters in the sediments the temperature is a surprising 15.3°C; the hydrostatic pressure has increased in the pore water of the sediment by 10.5 kg/cm^2. The temperature and pressure corrections (both positive) from Wilson's tables for the speed of sound in sea water indicate an increase in sound velocity (due solely to these two factors) of 53 m/sec from the sediment surface to a depth of 100 meters within the sediment.

Within homogeneous sea-floor sediments there are at least four important factors resulting in sound-velocity gradients. The effects of temperature and hydrostatic pressure in the water have been noted above. Two others are the decrease in sediment porosity resulting from the intergranular pressures of the sediment mineral grains (overburden pressure) and those components of sediment strength resulting in rigidity of the sediment structure (increasing cohesion, cementation, etc.). The increase of sound speed with decrease of porosity or pore space in marine sediments is mainly due to the large effect of water compressibility; it has been the subject of numerous papers[33,34,39-42] and will not be reviewed here.

When a sediment sample is removed from a bore hole to the laboratory, it undergoes a small increase in porosity and decrease in cohesion, as a result of expansion caused by reduction in intergranular pressure. The sample never expands enough to return to the porosity or cohesion it had when it was at the sediment surface prior to burial and imposition of intergranular pressures. Therefore, when correcting laboratory measurements of sound speed to *in situ* conditions at depth in the sediment, there is an increment for decrease in porosity (because of overburden pressure) which can be estimated with probable accuracy, and an increment owing to increased cohesion, which at the present time cannot be estimated with accuracy. These porosity corrections are best estimated from soil-mechanics consolidation tests; such tests were made on the Mohole sediments.[9]

The laboratory measurements of the velocity of sound in the Mohole samples have been corrected to *in situ* conditions in the sediment body using the sum of three corrections discussed above: temperature, hydrostatic pressure in the pore water, and porosity-pressure effects. These corrections do not include any factor of increased sound speed owing to increased cohesion (in this case probably small), and are thus minimum corrections. The resulting *in situ* sound speeds are listed in table 8 and plotted against depth in the sediment in figure 4.

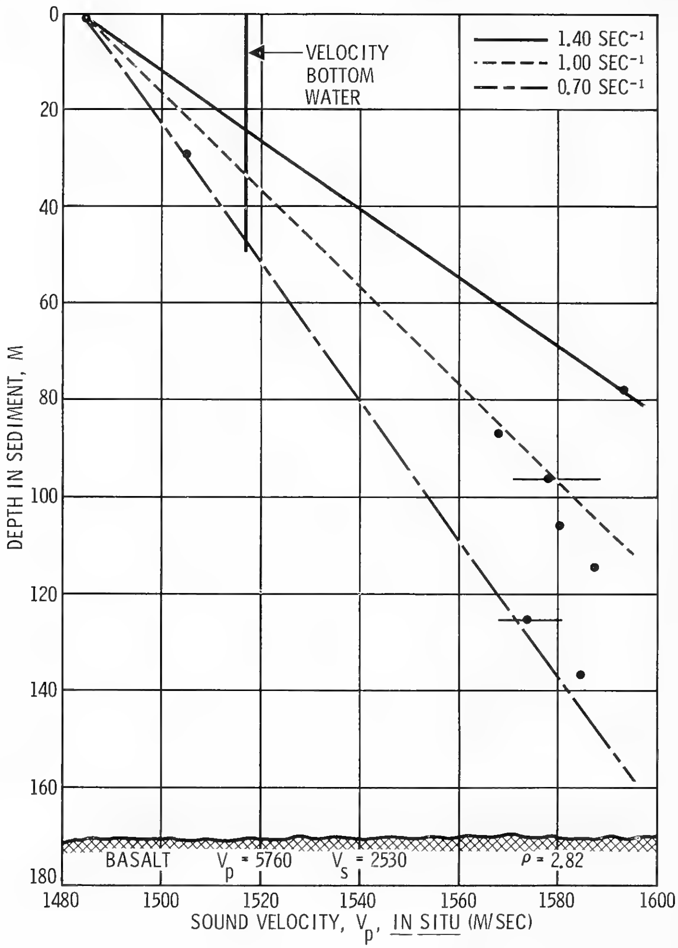

Figure 4. In situ sound velocity vs depth in sediment at the Mohole (Guadalupe Site). Data on basalt from Somerton et al.[29]

Following the reasoning and computations discussed in the first section (shallow Bering Sea), some elastic properties of the surficial sediments have been computed; they are included in table 4.

SOUND-VELOCITY GRADIENTS

The velocity of sound in the Mohole sediments just below the water-sediment interface (1484 m/sec) is about 2.2 percent less than the velocity in the sea water just above the bottom (1517 m/sec). (This is a commonly observed phenomenon for this type of high-porosity deep-sea clay.) This value compares with the 2.4 percent computed by Fry and Raitt in the area, and that measured from the TRIESTE in the San Diego Trough (2.3 percent).[35,5]

Vertical sound-velocity gradients in deep-sea sediments appear to lie between 0.5 and 2.0 sec^{-1}, with most values between 0.9 and 1.4 sec^{-1}.[43-45] The balance of evidence indicates that the corresponding velocity-vs-depth relationship is parabolic or exponential rather than linear in form, but there is insufficient evidence on which to make a decision. Several constant gradients have been indicated by dashed lines on figure 4. Apparently the vertical sound-velocity gradient, as reconstructed by these samples, lies between 0.7 and 1.4 sec^{-1}, with an average near 1.0 sec^{-1}. If 1.0 sec^{-1} is used, an interval velocity of 1569 m/sec is derived, which compares favorably with the value of 1.6 km/sec which was computed from the seismic reflection surveys and the drilled thickness.[28] A linear velocity equation for the area, of the form

$$\text{Velocity at depth, } Z, \; V_Z = V_o + KZ$$

would be

$$V_Z = 1484 + 1.0(Z)$$

where

V_o = velocity at sediment surface in m/sec,

K = velocity gradient,

Z = depth in the sediment in meters.

A vertical line from the bottom-water velocity (1517 m/sec, fig. 4) intersects the probable sound-velocity gradients between 20 and 45 meters, thus predicting the thickness of the layer in which the velocity of sound is less in the sediment than in the water just above the bottom. These thicknesses are in accordance with those noted in the Atlantic.[46,47]

The sediment surface at the Mohole Site is red clay; at the first cored depth in the hole (EM 8-1) at 29 meters, it is distinctly different: a clayey silt. The thickness of the red clay is indeterminate; gravity cores in the area were all red clay between 1 and 2 meters in length. Rittenberg et al. note that red clay cores to the north and south rarely contain more than 1 meter of red clay, and that, allowing for compaction in the gravity cores, the red clay might be no more than 2.5 meters thick.[32] Krause notes that on the echo-sounder record there is a strong reflector (or "double bottom") at a depth of 5 to 7 meters in the area.[27] It is a distinct possibility that the "double bottom" marks the lower limit of the red clay but other possibilities, such as ash layers, cannot be excluded.

SUMMARY

For either theoretical or experimental studies of sound in relation to the sea floor, it is necessary to choose a model, or models, of the upper few tens of feet in the sediment and rocks of the sea floor. In the past, a wide variety of these models have been postulated; some are valid and some are not worthy of consideration.

In the first part of this report the information necessary to form a valid geoacoustic model of the sea floor was listed. These items will not be repeated here, but, in general, the following are essential: (1) a detailed topographic chart based on electronically determined ship's positions, (2) sub-bottom layering within the sediment body in sufficient

detail to show the prominent reflectors in the upper few tens of feet, and (3) enough measurements (preferably *in situ*) to establish the lateral and vertical gradients of those properties having effects on sound propagation. All of these items are now within technological feasibility.

Sub-bottom layering in the detail required is not feasible using the spark-source type of sub-bottom acoustic reflection equipment; that part of principal interest is a mere black line on the record. The direction of research and development to obtain the required information should lie with deep-towed transducers and/or equipment mounted on deep submersibles.

The information on mass physical properties of sediments, in the detail required, can best be obtained from *in situ* measurements either from probes, bore holes, or from submersibles; these measurements can also validate those taken from surface ships, or in the laboratory. Those properties in most need of study at present are the velocity of the elastic shear wave, and the attenuation of sound at frequencies of interest in underwater acoustics. Studies of the compressional wave, and density, are well advanced, and the values of these properties can usually be predicted with some accuracy. More study, however, is needed of the vertical gradients of these properties.

The two geoacoustic models which were developed contrast strongly.

The Bering Sea area reported here is extremely flat and is covered with a fine, hard sand, in which the sound speed is from 4 to 12 percent greater than in the sea water just above the bottom; the density varies from 1.82 to 1.93 g/cc. In general, there is about 5 to 50 feet of sediment overlying a prominent reflector ("rock").

In situ sound speeds at the Mohole Site vary from 1484 m/sec at the sediment surface to 1584 m/sec at a depth in the sediment of 136 meters. The resulting sound-velocity gradient is approximately 1.0 sec^{-1}; the interval

velocity is about 1565 m/sec. Sound speed in the surficial sediment is about 2.2 percent less than in the water just above the sea floor.

RECOMMENDATIONS

1. When underwater sound experiments involve bottom-bounce propagation, a realistic geoacoustic model of the sea floor should be derived from surveys, measurements, and studies made, or taken, at or about the time of the acoustic experiments. Preferably, the insonified area should be designated by the person in charge of the acoustic experiments. In an expedition into far areas, the oceanographers should be an integral part of the scientific personnel aboard the ship, or ships, conducting the experiments. Geoacoustic models of the sea floor should be published in a continuing series to aid studies of underwater sound propagation.

2. Increasing use should be made of *in situ* measurements made from research submersibles. Studies need to be continued of methods which allow the prediction of *in situ* values from laboratory or surface-ship measurements.

3. Detailed layering within the upper part of the sediment body should be determined on the scale of tens of feet. At the present time this can be done from surface ships in waters a few hundred feet deep, but in the deep sea, present technology appears to indicate use of deep submersibles, or deeply-towed transducers, although other methods are possible.

4. Future research programs involving the mass physical properties of sediments, if intended to support

underwater acoustic research, should emphasize the speed and attenuation of elastic, compressional, and shear waves; special attention needs to be directed to the vertical gradients of these properties and of a few others such as density and porosity.

5. Studies involving sedimentary processes and the areal distributions of sediments should be encouraged because a thorough knowledge of these aspects of sediment bodies will, in the end, be the key to prediction of geoacoustic properties over large areas and with depth in the sea floor.

REFERENCES

1. Ewing, W. M. and others, Elastic Waves in Layered Media, McGraw-Hill, 1957

2. Hersey, J. B., "Continuous Reflection Profiling," p. 47-72 in Hill, M. N., The Sea; Ideas and Observations on Progress in the Study of the Seas, v. 3: The Earth Beneath the Sea, History, Interscience Publishers, 1963

3. Menard, H. W., Marine Geology of the Pacific, McGraw-Hill, 1964

4. Moore, D. G., "Acoustic-Reflection Studies of the Continental Shelf and Slope Off Southern California," Geological Society of America. Bulletin, v. 71, p. 1121-1136, August 1960

5. Hamilton, E. L., "Sediment Sound Velocity Measurements Made *in situ* From Bathyscaph TRIESTE," Journal of Geophysical Research, v. 68, p. 5991-5998, 1 November 1963

6. Wilson, W. D., "Speed of Sound in Sea Water as a Function of Temperature, Pressure, and Salinity," Acoustical Society of America. Journal, v. 32, p. 641-644, June 1960

7. Wilson, W. D., "Equation for the Speed of Sound in Sea Water," Acoustical Society of America. Journal, v. 32, p. 1357, October 1960

8. U. S. Naval Oceanographic Office Special Publication 58, Tables of Sound Speed in Sea Water, 1962

9. Hamilton, E. L., "Consolidation Characteristics and Related Properties of Sediments From Experimental Mohole (Guadalupe Site)," Journal of Geophysical Research, v. 69, p. 4257-4269, 15 October 1964

10. Moore, D. G., "Acoustic-Reflection Reconnaissance of Continental Shelves: Eastern Bering and Chukchi Seas," p. 319-362 in Miller, R. L., ed., Papers in Marine Geology: Shepard Commemorative Volume, Macmillan, 1964

11. Shumway, G. and others, "Fairway Rock in Bering Strait," p. 401-407 in Miller, R. L., ed., Papers in Marine Geology: Shepard Commemorative Volume, Macmillan, 1964

12. Navy Electronics Laboratory Report 916, Arctic SCUBA Diving, 1958. I: Observations on the Alaskan Arctic Shelf and Under Ice in the Polar Sea; II: Notes on the Arctic Diving Operation, by G. Shumway and J. A. Beagles, 17 August 1959

13. Bucker, H. P., "Normal-Mode Sound Propagation in Shallow Water," Acoustical Society of America. Journal, v. 36, p. 251-258, February 1964

14. Navy Electronics Laboratory Technical Memorandum 563, Frequency Spectrum of Explosive Charges Fired in Shallow Water, by D. L. Keir, 20 September 1962*

15. Mackenzie, K. V., "Long-Range Shallow-Water Transmission Measurements (Abstract)," Acoustical Society of America. Journal, v. 36, p. 1014, May 1964

16. Navy Electronics Laboratory Report 1160, LORAD Tests in the Shallow Bering Sea, by J. A. Whitney, CONFIDENTIAL, 27 February 1963

17. Navy Electronics Laboratory Report 204, Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949, Pt. 1: Sea Floor Studies, by E. C. Buffington and others, 2 October 1950

REFERENCES (Continued)

18. Dietz, R. S. and others, "Sediments and Topography of the Alaskan Shelves," p. 241-256 in Miller, R. L., ed., Papers in Marine Geology: Shepard Commemorative Volume, Macmillan, 1964

19. Adams, L. H., "Elastic Properties of Materials of the Earth's Crust," p. 50-80 in Gutenberg, B., ed., Internal Constitution of the Earth, 2d ed., Dover, 1951

20. Birch, F., "The Velocity of Compressional Waves in Rocks to 10 Kilobars, Part 2," Journal of Geophysical Research, v. 66, p. 2199-2224, July 1961

21. Urick, R. J., "A Sound Velocity Method for Determining the Compressibility of Finely Divided Substances," Journal of Applied Physics, v. 18, p. 983-987, November 1947

22. Urick, R. J. and Ament, W. S., "The Propagation of Sound in Composite Media," Acoustical Society of America. Journal, v. 21, p. 115-119, March 1949

23. Gassman, F., "Über die Elastizität Poröser Medien," Naturforschenden Gesellschaft in Zürich. Vierteljahrsschrift, v. 96, p. 1-23, 1951

24. Hamilton, E. L., "Sound Speed and Related Physical Properties of Sediments From Experimental Mohole (Guadalupe Site)," Geophysics, v. 30, 1965 (In Press)

25. Igelman, K. R. and Hamilton, E. L., "Bulk Densities of Mineral Grains From Mohole Samples (Guadalupe Site)," Journal of Sedimentary Petrology, v. 33, p. 474-478, June 1963

26. Moore, D. G., "Shear Strength and Related Properties of Sediments From Experimental Mohole (Guadalupe Site)," Journal of Geophysical Research, v. 69, p. 4271-4291, 15 October 1964

27. Krause, D. C., "Geology of the Sea Floor East of Guadalupe Island," Deep-Sea Research, v. 8, p. 28-38, 1961

28. National Research Council. AMSOC Committee, Experimental Drilling in Deep Water at La Jolla and Guadalupe Sites, Washington, National Academy of Sciences-National Research Council, 1961 (National Research Council Publication 914)

29. Somerton, W. H. and others, "Physical Properties of Mohole Test Site Basalt," Journal of Geophysical Research, v. 68, p. 849-856, 1 February 1963

30. Shor, G. G., Jr. and others, "Deep-Sea Tests of a New Nonexplosive Reflection Profiler," Journal of Geophysical Research, v. 68, p. 1567-1571, 1 March 1963

31. Riedel, W. R. and others, "Preliminary Drilling Phase of Mohole Project, II: Summary of Coring Operations," American Association of Petroleum Geologists. Bulletin, v. 45, p. 1793-1798, November 1961

32. Rittenberg, S. C. and others, "Biogeochemistry of Sediments in Experimental Mohole," Journal of Sedimentary Petrology, v. 33, p. 140-172, March 1963

33. Shumway, G., "Sound Speed and Absorption Studies of Marine Sediments by a Resonance Method, Part I," Geophysics, v. 25, p. 451-467, April 1960

34. Shumway, G., "Sound Speed and Absorption Studies of Marine Sediments by a Resonance Method, Part II," Geophysics, v. 25, p. 659-682, June 1960

35. Fry, J. C. and Raitt, R. W., "Sound Velocities at the Surface of Deep Sea Sediments," Journal of Geophysical Research, v. 66, p. 589-597, February 1961

36. Gerard, R. and others, "Thermal Gradient Measurements in the Water and Bottom Sediment of the Western Atlantic," Journal of Geophysical Research, v. 67, p. 785-803, February 1962

37. Bullard, E. C., "The Flow of Heat Through the Floor of the Ocean," p. 218-232 in Hill, M. N., The Sea; Ideas and Observations on Progress in the Study of the Seas, v. 3: The Earth Beneath the Sea, History, Interscience Publishers, 1963

38. Von Herzen, R. P. and Maxwell, A. E., "Measurements of Heat Flow at the Preliminary Mohole Site Off Mexico," Journal of Geophysical Research, v. 69, p. 741-748, 15 February 1964

39. Hamilton, E. L. and others, "Acoustic and Other Physical Properties of Shallow-Water Sediments Off San Diego," Acoustical Society of America. Journal, v. 28, p. 1-15, January 1956

40. Laughton, A. S., "Sound Propagation in Compacted Ocean Sediments," Geophysics, v. 22, p. 233-260, April 1957

41. Nafe, J. E. and Drake, C. L., "Variation With Depth in Shallow and Deep Water Marine Sediments of Porosity, Density and the Velocities of Compressional and Shear Waves," Geophysics, v. 22, p. 523-552, July 1957

42. Sutton, G. H. and others, "Physical Analysis of Deep Sea Sediments," Geophysics, v. 22, p. 779-812, October 1957

43. Ewing, J. I. and Nafe, J. E., "The Unconsolidated Sediments," p. 73-84 in Hill, M. N., The Sea; Ideas and Observations on Progress in the Study of the Seas, v. 3: The Earth Beneath the Sea, History, Interscience Publishers, 1963

44. Nafe, J. E. and Drake, C. L., "Physical Properties of Marine Sediments," p. 794-815 in Hill, M. N., The Sea; Ideas and Observations on Progress in the Study of the Seas, v. 3: The Earth Beneath the Sea, History, Interscience Publishers, 1963

45. Houtz, R. E. and Ewing, J. I., "Detailed Sedimentary Velocities From Seismic Refraction Profiles in the Western North Atlantic," Journal of Geophysical Research, v. 68, p. 5233-5258, 15 September 1963

46. Officer, C. B., "A Deep-Sea Seismic Reflection Profile," Geophysics, v. 20, p. 270-282, April 1955

47. Katz, S. and Ewing, M., "Seismic-Refraction Measurements in the Atlantic Ocean, Part VII: Atlantic Ocean Basin, West of Bermuda," Geological Society of America. Bulletin, v. 67, p. 475-510, April 1956

48. Hamilton, E. L., "Data on Recent Marine Sediments," Geotimes, v. 7, p. 41-42, January-February 1963

49. Mackenzie, K. V., "Sound-Speed Measurements Utilizing the Bathyscaph TRIESTE," Acoustical Society of America. Journal, v. 33, p. 1113-1119, August 1961

50. Naval Ordnance Laboratory Report 6747, Tables for the Speed of Sound in Distilled Water and in Sea Water, by W. D. Wilson, 13 November 1959

51. Navy Electronics Laboratory Report 416, v. 2, Oceanographic Cruise to the Bering and Chukchi Seas, Summer 1949: Part IV, Physical Oceanographic Studies: v. 2, Data Report, by J. F. T. Saur and others, 27 May 1954

52. U. S. Navy Hydrographic Office Publication 614, Processing Oceanographic Data, by E. C. LaFond, 1951

53. Shepard, F. P., "Nomenclature Based on Sand-Silt-Clay Ratios," Journal of Sedimentary Petrology, v. 24, p. 151-158, September 1954

54. Navy Electronics Laboratory Technical Memorandum 596, Sediment Sound Speed Measurements *in situ* From Bathyscaph TRIESTE, by E. L. Hamilton, 28 March 1963*

---

* NEL Technical Memoranda are informal documents intended primarily for use within the Laboratory.

APPENDIX A: INFORMATION ON SEDIMENTS NEEDED FOR IDEAL GEOACOUSTIC MODEL

A. Location, ship, and equipment data.

1. Sample identification: station and sample numbers, ship, expedition, personnel.

2. Geographic data: latitude, longitude, date, time, water depth (echo sounder, true, or corrected).

3. Sampling equipment used (description or cross reference).

4. Operation of sampling (if anything unusual).

5. Field descriptions of results, including description of sediment or rock samples, degree of disturbance and recovery, etc.

B. Laboratory measurements, analyses, and computations (designed to yield lateral and vertical gradients of the properties noted).

1. Grain size analysis, to yield median diameter percentages of sand, silt, and clay, and sediment nomenclature (*e.g.*, "silty clay").

2. Porosity.

3. Density.

a. Saturated, or bulk;

b. Of solids (minerals);

c. Of interstitial water.

4. Static shear strength (soil mechanics test).

5. Consolidation characteristics (soil mechanics test).

6. Sediment solid constituents.

a. Minerals.

b. Biological.

c. Organic.

7. Rate of sediment accumulation.

8. Sound-speed measurements.

a. Speed of compressional wave.

b. Speed of shear wave.

9. Attenuation of sound (50 c/s to 10 kc/s).

10. Computations or measurements of elastic properties including compressibility, shear modulus, Young's Modulus, Lamé's Constant, Poisson's Ratio.

11. Bottom-water characteristics including: pressure, temperature, salinity, sound speed, density.

12. Sediment surface roughness and uniformity on a microscale; animals, rocks and minerals littering sediment surface (as seen by lowered camera, or by eye and camera from submersible); animal-population counts and degree of surface disturbance by bottom dwellers.

13. Overburden pressures with depth in the sediment.

14. Temperature gradient within the sediment.

It is emphasized that this is an ideal list and that all of these properties are, at present, not determinable with present technology or ability to measure. Most measurements which can be done *in situ* by lowered equipment, from a submersible, or by logging in a drilled hole are preferable to laboratory measurements, although the latter are needed for associated studies, especially for future prediction. Sediment sampling and bottom observations can usually be most efficiently done from a submersible, but in any event, great care should be exercised to get a "least disturbed" sample with a properly designed sampler, and to carefully preserve it under lowered temperature and with 100 percent saturation (e.g., small samples under sea water within a refrigerator).

Two of the items above -- static shear strength (soil mechanics test), and consolidation characteristics (soil mechanics test) -- are of principal utility in computations of sea-floor bearing capacity and stability as applied to bottomed equipment (such as an array). Consolidation tests are also used, as noted in the discussion of the Mohole model, to estimate *in situ* porosities within the sediment, which are closely connected with sound speed.

Information other than sediment properties needed for an ideal geoacoustic model are noted in the main text (pp. 6-12).

APPENDIX B: CODE USED TO TRANSMIT ENVIRONMENTAL INFORMATION DURING BERING AND CHUKCHI SEAS EXPEDITION, 1960

As noted in the main text, a special, prearranged code was used to transmit sea-floor environmental information by radio from the R/V HUGH M. SMITH to the following ships. Two such messages were actually sent for two survey lines, S_1 and S_2, in the Bering Sea. The third line, S_3, in the Chukchi Sea, was not surveyed because of the ice pack which was encountered about 50 miles farther south than anticipated.

The following memorandum is reproduced verbatim from records of the expedition:

June 1960

From: E. L. Hamilton To: K. V. Mackenzie

Subject: Transmission of information, Summer 1960.

1. Tracks: S_1 = "A"; S_2 = "B"; S_3 = "C".

2. Point along track in nautical miles from the south end follows track letter.

Ex: A67 = track A, 67 miles from south end.

3. Sediment thickness in feet.

"T" followed by numbers in feet.

TI = thick sediment section with no prominent reflectors.

TX = no thickness figure available.

TR = rock at surface.

Ex: T1500 = sediment thickness 1500 feet over prominent reflector.

Note: When data are given at two points, it is understood that conditions between the points are the same, or changing in a regular manner. Examples: A67T300A75T500, means that the reflecting surface is dipping regularly toward the second point. A91TRA110TR means that rock is at the surface between 91 and 110 miles.

4. Roughness of basement.

Given by a series of "A's" and "T's."

5. Sediment type (using API-Shepard (1954) diagram).

"S" followed by one digit

0-gravel; 1-sand; 2-silty-sand; 3-sandy-silt; 4-silt; 5-sand-silt-clay; 6-clayey-sand; 7-sandy clay; 8-clayey-silt; 9-silty-clay; 10-clay; 11-glacial marine (mixture of various types above); 12-rock; 13-silty-sand, or sandy-silt with abundant shell fragments.

6. Sound velocity in sediments (measured *in situ* by diver-handled probes).

"V" followed by three digits; Ex: V515 means velocity is 5150 ft/sec (this gives it to nearest 10 feet/sec).

7. Ratio of sound velocity in sediments/sound velocity in bottom water.

"P" followed by three digits with decimal understood between 1st and 2nd digit. Ex: P103 means vel. in sed/vel. water = 1.03

8. Density of the surficial bottom sediments.

"D" followed by three digits with decimal understood between 1st and 2nd digit. Note: density will be estimated.

9. Attenuation in the surficial sediments.

"Y" followed by three digits with the decimal understood between the 2nd and 3rd digit (units are in dB/ft) followed by "K" and three digits with the decimal understood between the second and third digits (units are kilocycles).

Sample message:

"A85T340S4V510P102D160Y153K183"

Means: "At a point 85 miles from the southern end of line S_1, the thickness of sediment over a prominent reflector is 340 feet; the sediment type is silt; the velocity of sound in the sediment (from the *in situ* velocity meter) is 5100 ft/sec; the ratio of velocity in sediment to that in the bottom water is 1.02; the density of the surface sediment is estimated to be about 1.60 gr/cc; the attenuation of sound in the surface sediments (from *in situ* meter is 15.3 dB/ft at 18.3 kc."

Notes:

(1) In the same message it is understood that a new point is being reported when the letter "A" appears again (or "B" or "C," depending on the line).

(2) It is planned to report one whole line when the work is done on that line.

(3) A series of "A's" and "T's" will give relief along the track.

Not all points will contain all the data -- these, of course, will only be given where we have stopped on station.

(4) If the detail of topography of the buried reflector is deeper beneath the sediment than 50 feet, the roughness will be generalized.

(5) When "E" appears after any letter it means that the data are estimated.

(6) We expect to run into ice along the northern part of S_3; when we have to finish the survey owing to ice, or any other conditions, we will terminate the last message with "F."

Navy Electronics Lab., San Diego, Calif.
Report 1283

GEOACOUSTIC MODELS OF THE SEA FLOOR: 1. SHALLOW BERING SEA; 2. MOHOLE (GUADALUPE SITE), by E. L. Hamilton, 52 p., 19 Apr 65.

UNCLASSIFIED

The information and technology necessary to derive a valid geological-geophysical-acoustic model of the sea floor are presented. Two contrasting models are detailed and discussed: one in the Bering Sea which has a shallow-water, high-velocity, hard-sand bottom; and the Mohole (Guadalupe Site) model which has a deep-water, low-velocity, soft-clay bottom.

Other models are to be reported in a continuing series.

1. Ocean bottom - Acoustic properties
2. Ocean bottom - Bering Sea
3. Mohole

I. Hamilton, E. L.

SR 004 03 01, Task 0539
(NEL L40151)

This card is UNCLASSIFIED

Navy Electronics Lab., San Diego, Calif.
Report 1283

GEOACOUSTIC MODELS OF THE SEA FLOOR: 1. SHALLOW BERING SEA; 2. MOHOLE (GUADALUPE SITE), by E. L. Hamilton, 52 p., 19 Apr 65.

UNCLASSIFIED

The information and technology necessary to derive a valid geological-geophysical-acoustic model of the sea floor are presented. Two contrasting models are detailed and discussed: one in the Bering Sea which has a shallow-water, high-velocity, hard-sand bottom; and the Mohole (Guadalupe Site) model which has a deep-water, low-velocity, soft-clay bottom.

Other models are to be reported in a continuing series.

1. Ocean bottom - Acoustic properties
2. Ocean bottom - Bering Sea
3. Mohole

I. Hamilton, E. L.

SR 004 03 01, Task 0539
(NEL L40151)

This card is UNCLASSIFIED

Navy Electronics Lab., San Diego, Calif.
Report 1283

GEOACOUSTIC MODELS OF THE SEA FLOOR: 1. SHALLOW BERING SEA; 2. MOHOLE (GUADALUPE SITE), by E. L. Hamilton, 52 p., 19 Apr 65.

UNCLASSIFIED

The information and technology necessary to derive a valid geological-geophysical-acoustic model of the sea floor are presented. Two contrasting models are detailed and discussed: one in the Bering Sea which has a shallow-water, high-velocity, hard-sand bottom; and the Mohole (Guadalupe Site) model which has a deep-water, low-velocity, soft-clay bottom.

Other models are to be reported in a continuing series.

1. Ocean bottom - Acoustic properties
2. Ocean bottom - Bering Sea
3. Mohole

I. Hamilton, E. L.

SR 004 03 01, Task 0539
(NEL L40151)

This card is UNCLASSIFIED

Navy Electronics Lab., San Diego, Calif.
Report 1283

GEOACOUSTIC MODELS OF THE SEA FLOOR: 1. SHALLOW BERING SEA; 2. MOHOLE (GUADALUPE SITE), by E. L. Hamilton, 52 p., 19 Apr 65.

UNCLASSIFIED

The information and technology necessary to derive a valid geological-geophysical-acoustic model of the sea floor are presented. Two contrasting models are detailed and discussed: one in the Bering Sea which has a shallow-water, high-velocity, hard-sand bottom; and the Mohole (Guadalupe Site) model which has a deep-water, low-velocity, soft-clay bottom.

Other models are to be reported in a continuing series.

1. Ocean bottom - Acoustic properties
2. Ocean bottom - Bering Sea
3. Mohole

I. Hamilton, E. L.

SR 004 03 01, Task 0539
(NEL L40151)

This card is UNCLASSIFIED

INITIAL DISTRIBUTION LIST

CHIEF, BUREAU OF SHIPS
  CODE 1620
  CODE 210L (2)
  CODE 240C (2)
  CODE 320
  CODE 360
  CODE 452E
  CODE 670 (2)
CHIEF, BUREAU OF NAVAL WEAPONS
  DLI-3
  DLI-31
  FASS
  R-56
  RU-222
  RUDC-2
  RUDC-11
CHIEF, BUREAU OF YARDS AND DOCKS
CHIEF OF NAVAL PERSONNEL
  PERS 118
CHIEF OF NAVAL OPERATIONS
  OP-07T
  OP-701E1
  OP-71
  OP-76C
  OP-03EG
  OP-09B5
CHIEF OF NAVAL RESEARCH
  CODE 416
  CODE 466
  CODE 468
COMMANDER IN CHIEF US PACIFIC FLEET
COMMANDER IN CHIEF US ATLANTIC FLEET
COMMANDER OPERATIONAL TEST AND
  EVALUATION FORCE
DEPUTY COMMANDER OPERATIONAL TEST -
  EVALUATION FORCE, PACIFIC
COMMANDER CRUISER-DESTROYER FORCE,
  US ATLANTIC FLEET
  US PACIFIC FLEET
COMMANDER TRAINING COMMAND
  US PACIFIC FLEET
OCEANOGRAPHIC SYSTEM PACIFIC (2)
COMMANDER SUBMARINE DEVELOPMENT
  GROUP TWO
FLEET AIR WINGS, ATLANTIC FLEET
  SCIENTIFIC ADVISORY TEAM
US NAVAL AIR DEVELOPMENT CENTER
  NADC LIBRARY
US NAVAL MISSILE CENTER
  TECH. LIBRARY, CODE NO 3022
PACIFIC MISSILE RANGE /CODE 3250/
US NAVAL ORDNANCE LABORATORY
  LIBRARY
US NAVAL ORDNANCE TEST STATION
  PASADENA ANNEX LIBRARY
  CHINA LAKE
US NAVAL WEAPONS LABORATORY
  KXL
PORTSMOUTH NAVAL SHIPYARD
PUGET SOUND NAVAL SHIPYARD
SAN FRANCISCO NAVAL SHIPYARD (2)
USN RADIOLOGICAL DEFENSE LABORATORY
DAVID TAYLOR MODEL BASIN
  APPLIED MATHEMATICS LABORATORY (2)
  /LIBRARY/
US NAVY MINE DEFENSE LABORATORY
US NAVAL TRAINING DEVICE CENTER
  CODE 365H, ASW DIVISION
USN UNDERWATER SOUND LABORATORY
  LIBRARY (3)
ATLANTIC FLEET ASW TACTICAL SCHOOL
USN MARINE ENGINEERING LABORATORY
US NAVAL CIVIL ENGINEERING LAB.
  L54
US NAVAL RESEARCH LABORATORY
  CODE 2027
  CODE 5120
US NAVAL ORDNANCE LABORATORY
  CORONA
USN UNDERWATER SOUND REFERENCE LAB.
BEACH JUMPER UNIT TWO
US FLEET ASW SCHOOL
US FLEET SONAR SCHOOL
USN UNDERWATER ORDNANCE STATION
OFFICE OF NAVAL RESEARCH
  PASADENA
US NAVAL SHIP MISSILE SYSTEMS
  ENGINEERING STATION
USN WEATHER RESEARCH FACILITY
US NAVAL OCEANOGRAPHIC OFFICE (2)
SUPERVISOR OF SHIPBUILDING US NAVY
  GROTON
US NAVAL POSTGRADUATE SCHOOL
  LIBRARY (2)
  DEPT. OF ENVIRONMENTAL SCIENCES
OFFICE OF NAVAL RESEARCH
  LONDON
  BOSTON
  CHICAGO
  SAN FRANCISCO
FLEET NUMERICAL WEATHER FACILITY
US NAVAL APPLIED SCIENCE LABORATORY
  CODE 9832
US NAVAL ACADEMY
ASSISTANT SECRETARY OF THE NAVY R-D
ONR SCIENTIFIC LIAISON OFFICER
  WOODS HOLE OCEANOGRAPHIC INSTITUTION
INSTITUTE OF NAVAL STUDIES
  LIBRARY
AIR DEVELOPMENT SQUADRON ONE /VX-1/
DEFENSE DOCUMENTATION CENTER (20)
DOD RESEARCH AND ENGINEERING
  TECHNICAL LIBRARY
DEFENSE ATOMIC SUPPORT AGENCY
NATIONAL OCEANOGRAPHIC DATA CENTER (2)
NASA
  LANGLEY RESEARCH CENTER (3)
COMMITTEE ON UNDERSEA WARFARE
US COAST GUARD
  OCEANOGRAPHY - METEOROLOGY BRANCH
ARCTIC RESEARCH LABORATORY
WOODS HOLE OCEANOGRAPHIC INSTITUTION
US COAST AND GEODETIC SURVEY
  MARINE DATA DIVISION /ATTN-22/ (3)
US WEATHER BUREAU
US GEOLOGICAL SURVEY LIBRARY
  DENVER SECTION
US BUREAU OF COMMERCIAL FISHERIES
  LA JOLLA DR. AHLSTROM
  WASHINGTON 25, D. C.
  POINT LOMA STATION
  WOODS HOLE, MASSACHUSETTS
  HONOLULU-JOHN C MARR
  LA JOLLA, CALIFORNIA
  HONOLULU, HAWAII
  STANFORD, CALIFORNIA
  POINT LOMA STA-J. H. JOHNSON
ABERDEEN PROVING GROUND, MARYLAND
REDSTONE SCIENTIFIC INFORMATION
  CENTER
BEACH EROSION BOARD
  CORPS OF ENGINEERS, US ARMY
EDGEWOOD ARSENAL
DEPUTY CHIEF OF STAFF, US AIR FORCE
  AFRST-SC
STRATEGIC AIR COMMAND
HQ AIR WEATHER SERVICE
UNIVERSITY OF MIAMI
  THE MARINE LAB. LIBRARY (3)
COLUMBIA UNIVERSITY
  HUDSON LABORATORIES
LAMONT GEOLOGICAL OBSERVATORY
DARTMOUTH COLLEGE
  THAYER SCHOOL OF ENGINEERING
  RADIOPHYSICS LABORATORY
RUTGERS UNIVERSITY
CORNELL UNIVERSITY
OREGON STATE UNIVERSITY
  DEPARTMENT OF OCEANOGRAPHY
UNIVERSITY OF SOUTHERN CALIFORNIA
  ALLAN HANCOCK FOUNDATION
UNIVERSITY OF WASHINGTON
  DEPARTMENT OF OCEANOGRAPHY
  FISHERIES-OCEANOGRAPHY LIBRARY
NEW YORK UNIVERSITY
  DEPT OF METEOROLOGY - OCEANOGRAPHY
UNIVERSITY OF MICHIGAN
  DR. JOHN C. AYERS (2)
UNIVERSITY OF ALASKA
  GEOPHYSICAL INSTITUTE
UNIVERSITY OF RHODE ISLAND
  NARRAGANSETT MARINE LABORATORY
YALE UNIVERSITY
  BINGHAM OCEANOGRAPHIC LABORATORY
FLORIDA STATE UNIVERSITY
  OCEANOGRAPHIC INSTITUTE
UNIVERSITY OF HAWAII
  HAWAII INSTITUTE OF GEOPHYSICS
  ELECTRICAL ENGINEERING DEPT
A-M COLLEGE OF TEXAS
  DEPARTMENT OF OCEANOGRAPHY
THE UNIVERSITY OF TEXAS
  DEFENSE RESEARCH LABORATORY
HARVARD UNIVERSITY
SCRIPPS INSTITUTION OF OCEANOGRAPHY
  MARINE PHYSICAL LAB
UNIVERSITY OF CALIFORNIA
  ENGINEERING DEPARTMENT
UNIVERSITY OF CALIFORNIA, SAN DIEGO
  SIO
MASSACHUSETTS INST OF TECHNOLOGY
  ENGINEERING LIBRARY
THE JOHNS HOPKINS UNIVERSITY
  APPLIED PHYSICS LABORATORY
INSTITUTE FOR DEFENSE ANALYSIS